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Evaluation of environmental and anthropogenic influences on ambient background metal and metalloid concentrations in soil

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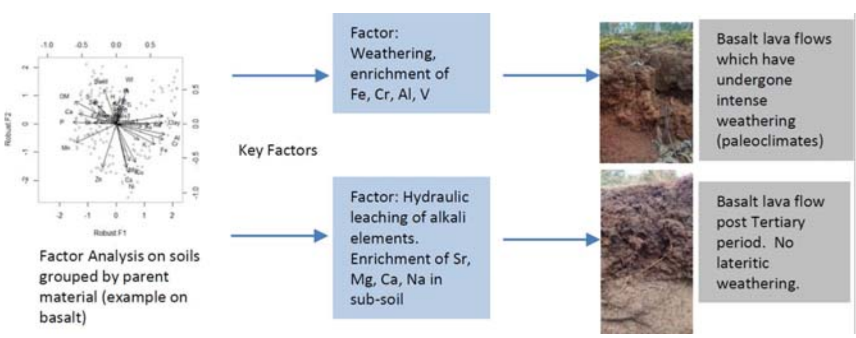
HIGHLIGHTS

- Environmental influences of enrichment of As, Cr, Cu, Ni, Pb and Zn in soil are presented.
- Expected ranges of background metals/metalloids in Victorian soils are presented.
- Lateritic weathering and illuviation are key influences on soil variability.
- Victorian soils are naturally enriched in As, Ni and Cr above background thresholds.
- Background Pb concentrations in soil were influenced by palaeoclimates.

GRAPHICAL ABSTRACT



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ABSTRACT

There has been a global shift in environmental risk assessment towards quantifying ambient background concentrations of metals/metalloids in soil. Whilst bedrock has been shown to be a key driver of metal/metalloid variability in soil, few researchers have assessed controls of ambient background concentrations in soils of similar bedrock. A soil survey was undertaken ofGreater Melbourne, Greater Geelong, Ballarat and Mitchell in Victoria, Australia for elements of potential environmental concern: As, Cd, Cr, Cu, Ni, Hg, Pb and Zn. Samples ($n = 622$) were collected from surface (0 to 0.1 m) and sub-surface (0.3 to 0.6 m) soils, overlying Tertiary-Quaternary basalt, Tertiary sediments and Silurian siltstone and sandstone. In addition, background soil data from open-source environmental assessment reports ($n = 5512$) were collated to support the understanding of natural enrichment, particularly at depths >0.6 m. Factor analysis, supported by correlation analysis and auxiliary geo-spatial data, provided an improved understanding of where and how background metal/metalloid enrichment occurs in the environment. Weathering during paleoclimates was the predominant influence of background metal/metalloid variability in soils overlying similar bedrock. Other key influences of metal/metalloid variability in soil included hydraulic leaching of alkali elements, biological cycling, topography and alluvial transfer of silt and sand from mineralised regions. In addition, urbanisation positively correlated with Pb and Zn concentrations in surface soils suggesting that anthropogenic activities may have resulted in diffuse Pb and Zn contamination of urban soil.

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1. Introduction

Due to the high variability of geogenic metal/metalloid concentrations in soil and multiple sources of potential anthropogenic contamination across the earth, it is often difficult to distinguish areas of geogenic enrichment from areas of anthropogenic enrichment (De Carlo et al., 2014; Myers and Thorbjornsen, 2004; Zhou and Xia, 2010). Metals/metalloids of geogenic (or natural) origin are typically less bioavailable than metals/metalloids of similar concentration associated with contamination, and therefore require different management practices (Palumboroe et al., 2005). Inaccurate characterisation of contamination versus natural enrichment can result in natural soils being disposed to landfill, limitations to land development and miss-understanding of potential risks to human health and the environment. Therefore, an understanding of where and why natural enrichment of metals/metalloids occurs in soils, at a land development scale (e.g.100 m × 100 m) or local scale (0.5–500 km^2), is integral for sustainable land management.

Human activities including the use of fossil fuels, mining and agriculture have resulted in diffuse additions of metals/metalloids to soils on a global scale (Cloy et al., 2008; Rosman et al., 1993). Although, the magnitude of diffuse contamination is typically low compared to the magnitude of natural variation (Fabian et al., 2017), the idea of a pristine soil reflecting true background concentrations of elements is no longer accurate. Therefore, for the purpose of understanding expected background metal/metalloid concentrations in soil, the term ambient background is used. Ambient background concentrations include the geogenic concentration (natural background) of elements and low level diffuse contamination from non-point, anthropogenic, sources (Mikkonen et al., 2017; Ottesen et al., 2008; Panno et al., 2006; Saaltink et al., 2014). As such, ambient background includes broad use of fertilizers from agricultural practices but excludes soils adjacent to roads, buildings and emission point sources, such as smelters (Darnley, 1995).

The natural concentration of elements of potential environmental concern (such as As, Cd, Cr, Cu, Ni, Hg, Pb, Zn) in soils is influenced by the parent material from which the soil has formed but also by environmental processes such as leaching, biological cycling, physical immobilisation and atmospheric deposition (Jenny, 1941; Reimann et al., 2015). Whilst the spatial variability of soil nutrients, at a local scale, has extensively been researched (Bogunovic et al., 2017; Gray et al., 2015; Guan et al., 2017; Uygur et al., 2010; Zhang et al., 2010), assessment of controls of trace element variability in soil is typically undertaken at broad (continental) scale.

Surveys of ambient concentrations of metals/metalloids have been undertaken around the world, including in Australia (de Caritat and Cooper, 2011), Asia (Cheng et al., 2014; Ohta et al., 2005), Europe (Reimann et al., 2014; Reimann et al., 2003; Salminen et al., 2005; Salminen et al., 2004) and the United States of America (Smith et al., 2014). These large datasets have enabled identification of key influences of metal/metalloid distribution on a global (Rauch, 2011), continental (0.5–50 million km^2), and regional scale (500–500,000 km^2) (Reimann et al., 2009; Reimann et al., 2011). These surveys have focussed on understanding the influence of underlying bedrock and mineralogy on trace element concentrations (de Caritat and Grunsky, 2013; Rauch, 2011), with little evaluation of environmental controls of variability in soils formed from similar parent materials at a local scale (i.e. the variability caused during pedogenesis).

de Caritat and Grunsky (2013) reviewed environmental controls of geochemical variability across Australia, based on catchment sediment samples collected during the National Geochemical Survey of Australia (NGSA). Key controls of soil variability at a continental scale, were reported to be; weathering of dominantly felsic rocks, weathering of dominantly mafic/ultramafic rocks, formation/preservation of regolith carbonates and evaporates, accumulation of resistant/heavy minerals and intense weathering (accumulation of Si and Zr) (de Caritat and Grunsky, 2013). The NGSA (de Caritat and Cooper, 2011) was undertaken at low resolution (frequency average of 1 sample site per 5500 km^2) and was not designed for identifying localised sources of metal/metalloid enrichment or contamination.

Globally, there has been a shift in environmental guidance, to include an understanding of background metal concentrations in soil when assessing environmental risk and the need for remediation (DEFRA, 2012; NEPC, 2013; Tarvainen and Jarva, 2011). Although continental scale surveys have provided an increased understanding of the distribution and variability of background metal concentrations in soils, it is recognised that regional assessments are required to assist in distinguishing natural enrichment from contamination, at the scale of environmental site assessments (Reimann and de Caritat, 2017).

The objectives of this study were to:

1. Establish ambient background concentration ranges of As, Cd, Cr, Cu, Hg, Ni, Pb and Zn in surface and sub-surface soils in targeted regions of Victoria.
2. Use multivariate statistical analysis to assess the influence of environmental and anthropogenic variables on ambient background metal/metalloid concentrations at a regional and local scale.
3. Compare regional background concentrations to the national background metal dataset (Reimann and de Caritat, 2017) to identify areas of natural enrichment.

2. Method

2.1. Study approach

This study involved the following steps; (i) soil survey to collect background data; (ii) collation of survey data and open-source soil data within the study area; (iii) statistical assessment of metal/metalloid concentrations; and (iv) correlation and factor analysis to support inference of environmental and anthropogenic controls of metal/metalloid variability in soil. The methods of assessment are described in the following sections.

2.2. The study area

Soils in Victoria have previously been reported to be naturally elevated in metals including Ni in soils overlying basalt (Mikkonen et al., 2017) and As in Silurian siltstone and sandstone (Meuser and Van de Graaff, 2011). The Study Area included soils overlying Tertiary-Quaternary basalt of the Newer Volcanics (basalt), Tertiary sediments (sediment), and Silurian siltstone and sandstone (siltstone/sandstone), in key areas of Victoria, Australia that have been identified for proposed residential growth and development; Greater Melbourne, Mitchell, Ballarat and Greater Geelong (Fig. 1). Greater Melbourne, with a population density of 4.49 people/ha is the largest city in Victoria. Mitchell is predominantly an agricultural area with a population density of 0.14 people/ha. Greater Geelong is a coastal based city with the second highest population density in Victoria of 1.87 people/ha and Ballarat is a regional city, with a rich history in gold mining, and population density of 1.38 people/ha (Australian Bureau of Statistics, 2016).

The topography of the Study Area was variable (Fig. 1), with rugged mountain ranges to the north east and east of Melbourne, low lying hills, recent alluvial sand terraces and wetlands to the south east of Melbourne and east of Greater Geelong, and basalt plains to the north and west of Melbourne (Boyce, 2013). The climate in the Study Area is temperate to semi-arid, including hot summers and mild winters, with mean annual rainfall varying from 534 mm/year in Geelong, in the south west of the Study Area, to 774 mm/year in Dandenong, in the east of the Study Area (BOM, 2016).

2.3. Soil survey

A background soil survey was undertaken. Samples were collected from 312 locations from surface (0.0 to 0.1 m) and sub-surface